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EVALUATING PENETRATION-MONITORING SYSTEMS*

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ABSTRACT

Evaluating the performance of a process monitoring system in detecting improper activities that could be related to material diversion requires a framework for addressing the complexity and statistical uncertainty of such systems. This report proposes a methodology that determines the optimal divertor strategy against a monitoring system and the system probability of detection. This method extends previous work by correctly modeling uncorrelated and correlated measurement errors for radiation monitors.

I. INTRODUCTION

A penetration monitoring system consists of an array of devices that monitor facility activities to detect improper movement of nuclear material and/or personnel through containment penetrations. The purpose of the monitoring is to prevent diversion of material by sensing environmental anomalies that could be related to a diversion attempt. Monitoring devices may detect material movement directly, as in the case of a radiation monitor, or may detect an improper activity such as a broken seal that indicates unauthorized access to an area. Applications of such a system could include assuring the continued validity of measurements for material previously measured and placed in storage; assuring that only declared transfers of material cross materials balance area boundaries so that materials accounting (MA) records are complete; and confirming the results of MA by monitoring penetrations that are potential diversion paths out of a facility.

Examples of facility containments are biological shielding, vault boundaries, or the outer structure of a facility. Penetrations in a containment could include personnel passages, process piping, or ventilation ducts. And penetrations are monitored by a variety of devices, such as motion or radiation detectors, sensitive to activities indicative of a diversion attempt.

Because of the potentially large numbers of penetrations in a facility[4] and the variety of instruments used to monitor them, there is a need for a methodology to evaluate and compare such complex and diverse systems in a coherent way. This report describes a method for evaluating the likelihood that a monitoring system will detect improper material movement through penetrations, considering all of the options available to a divertor in choosing diversion paths. This approach differs from previous analyses of this problem in that time-correlated errors in monitoring devices are modeled.[1,2,3] Information requirements for evaluating a monitoring system include an enumeration of penetrations that are credible diversion paths, the position of monitors along each path, and the likelihood of detection for each monitor as a function of the amount of material diverted. The results provide the optimal divertor strategy against the monitoring system and the system probability of detection against the strategy.

II. EVALUATION ISSUES

Analysis of a penetration monitoring system is complicated by the complexity of the system. In nuclear facilities such as a reprocessing plant the containment penetrations may number in the hundreds, and credibility analyses designed to eliminate unreasonable diversion paths may still leave many to be evaluated.[4] Further, because material can be moved through each penetration in multiple diversion attempts, the total number of diversion scenarios to be evaluated can become quite large.

Another level of complexity is introduced by the many types of devices that monitor the penetrations. These devices vary with the particular penetration and the form of the material that might move through the penetration, but all of them are designed to detect environmental anomalies indicating a diversion attempt. Some examples of such monitors are film cameras, CCTV, seals, motion detectors, and radiation detectors.

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the probability of detection, so the operator must balance these two factors in selecting T.

For a material amount D_j, representing the total amount to be diverted over path j and a specified number of attempts K_j, the probability that the divertor is not detected by the i^{th} instrument on path j is just the probability that no measurements exceed the threshold T, i.e., Prob ($M_1 \leq T$, --, $M_{K_j} \leq T$), which is

$$P(i_j, D_j, K_j) = \frac{1}{(2\pi)^{K/2}|\Sigma|^{1/2}}$$

$$\cdot \underbrace{\int_{\infty}^{T} \cdots \int_{\infty}^{T}}_{K_j} e^{-(M-D)\Sigma^{-1}(M-D)} dM$$

where M is the K_j-vector of measurements, $M = (M_1, \ldots, M_K)$, D is the K_j-vector of uniform diversion $D = (D_j/K_j, \ldots, D_j/K_j)$, and Σ is the covariance matrix of the measurements M.

The total probability that the system does not detect diversion is

$$\underset{i,j}{\pi}\, P(i_j, D_j, K_j)$$

where D_j is the amount allocated to the j^{th} path, K_j is the number of attempts over path j, and i_j ranges over the number of instruments on each path.

The divertor is assumed to know the measurement error variances of each instrument and the decision thresholds so that he can calculate the probability of detection for any diversion strategy. A strategy, which consists of specifying a material amount D_j and number of attempts K_j for each path j, is an optimal diversion strategy if it minimizes the detection probability while attaining a goal quantity of material. The probability of detection against the optimal strategy is taken as the measure of performance for the penetration monitoring system.

The optimal strategy can be found as the solution to the nonlinear optimization problem

$$\underset{D_j,\, K_j}{\text{maximize}} \quad \underset{i_j, j}{\pi}\, P(i_j, D_j, K_j) \tag{1}$$

subject to $\Sigma_j D_j = D$.

The solution to this problem has been found using dynamic programming,[3] which is an efficient method of searching for the optimal strategy (Appendix B). A computer program has been developed to implement the dynamic programming solution of (1). The program determines the amount to be diverted over each path and the number of attempts, and calculates the system probability of detecting this strategy.

IV. EXAMPLE

This method of evaluating a penetration monitoring system was developed to determine the effect of time-correlated errors on systems performance. The following example shows that the results can be sensitive to the treatment of such errors in modeling monitoring instruments. Consider a simplified facility with just two penetrations, each monitored by a single instrument having measurement errors as given in Table I. The maximum number of diversion attempts through each penetration is also given in the Table I.

TABLE I

Penetration	Instrument Error (%1σ) Precision	Instrument Error (%1σ) Calibration	Max. No. Attempts
1	6	4	30
2	4	0	10

In solving this problem to find the systems detection probability the measurement errors for the instrument at penetration 1 were treated in three different ways:

1. Using the correct values, $\sigma_r = 0.06$, $\sigma_n = 0.04$.

2. Treating the correlated error as an uncorrelated error, $\sigma_r = 0.072$, $\sigma_n = 0$.

3. Neglecting the correlated error, $\sigma_r = 0.06$, $\sigma_n = 0$.

The probability that the system detects diversion is shown in Fig. 2 for each of the three cases. These results indicate that either neglecting the correlated error or treating it as an uncorrelated error can overstate the systems sensitivity to diversion. Thus, in Fig. 2 the higher probabilities of detection for cases b and c do not reflect an actual performance improvement, but instead they are the result of incorrectly modeling the system.. In general the size of the overstatement will increase with the size of the correlated error and the number of diversion attempts.

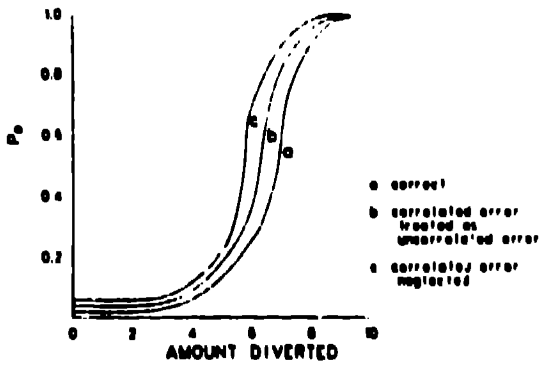

Fig. 2. Detection Sensitivity

APPENDIX A

Suppose that for path j the divertor has N opportunities to divert material and chooses to use K of these. The probability of not being detected by the i^{th} instrument on the path j is

$$P_{ij}(d_1, \ldots, d_K) = \frac{1}{(2\pi)^{K/2}|\Sigma|^{1/2}} \cdot \int_{-\infty}^{T_{ij}} \ldots \int_{-\infty}^{T_{ij}} e^{-(M-D)\Sigma^{-1}(M-D)} dM ,$$

where M is the K-vector of measurements (M_1, .., M_K), D is the K-vector of diverted amounts (d_1, ..., d_K), Σ is the covariance matrix of the measurements and T_{ij} is the decision threshold for each measurement.

We want to show that uniform diversion over path j is the optimal diversion strategy. Following the proof given in Ref. 1, note that each P_{ij} is log concave, and that interchanging d_m and d_n for any $m \neq n$ does not change the value of P_{ij}.

Let $p = (d_1^*, \ldots, d_K^*)$ be a diversion strategy that minimizes the probability of detection against instrument i on path j and observe that interchanging any pair d_m^*, d_n^*, $d_m^* \neq d_n^*$, will give another minimising diversion strategy $q = d_1^*$, ..., d_n^* ... d_m^*, ..., d_K^*) because the value of P_{ij} is unchanged by such a transformation. For any point r on the line segment connecting the points p and q in K-space, the strict concavity of log P_{ij} implies that the probability of detection at r is less than the probability of detection at p and q. This contradicts the minimality of the function at p and q, so that we must have p = q, i.e., $d_m^* = d_n^*$ for $1 \leq m$, $n < K$, and uniform diversion is optimal.

To find the optimal diversion strategy considering all instruments on path j the divertor wants to minimize the total probability of detection

$$\prod_{i=1}^{M} P_{ij}(d_1, \ldots, d_K)$$

or equivalently minimize

$$\sum_{i=1}^{M} \log P_{ij} (d_1, \ldots, d_K) \qquad \text{(A-1)}$$

Because each term in the sum is concave and has a value unchanged by interchanging any pair d_i, d_j, the function (A-1) also has these properties. The optimality of uniform diversion over path j follows exactly as in the proof for a single instrument.

APPENDIX B

To formulate the divertor problem as one that can be solved by dynamic programming let $F(j,d_j)$ be the probability of nondetection on path j when the total amount d_j is diverted using the optimal number of attempts on that path. Define the function G as

$$G(j,D_j) = \mathrm{MAX}_{d_j} [F(j,d_j) * G(j-1,D_j-d_j)]$$

$$G(1,D_j) = F(1,D_j)$$

where D_j is the total amount assigned to the paths 1, 2, ... i. G represents the probability of nondetection for the paths 1, 2, ... i.

The problem is solved by sequentially determining for each i the maximizing amount d_j given that a total D_j has been diverted over paths 1 through j. The optimal strategy for the divertor is determined from these values. This procedure finds the global maximum for the divertor problem. While the amount diverted must be calculated in discrete quantities, there is negligible loss of accuracy if units are chosen appropriately.

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